



Solar vs. Fission Surface Power for Mars

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Background

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- **2009: NASA's Design Reference Architecture 5.0 baseline fission surface power for a crewed Mars mission**
 - Two landers to one site, then two more landers to a different site
 - Solar power did not trade as well as fission power for mass
 - ✓ Fission development costs would be shared with the Constellation Program's lunar surface mission, making fission more attractive
- **2016: NASA revisited the solar vs. fission trade based on new information**
 - Paradigm shift to Evolvable Mars Campaign
 - ✓ Multiple landers to the same site, allowing infrastructure build-up
 - Technology advances since the original studies were performed
 - ✓ Kilopower fission system, higher density batteries, more efficient solar arrays



COMPASS Team

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The new study was performed by the NASA Glenn Research Center's Collaborative Modelling for Parametric Assessment of Space Systems (COMPASS) Team



NASA Glenn Research Center

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Additional Expertise

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Making Mars More Affordable Utilize Martian Resources

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- Mars Ascent Vehicle arrives on Mars with empty Liquid Oxygen propellant tanks
- Fission- or solar-powered In Situ Resource Utilization extracts carbon dioxide from the Martian atmosphere
 - ISRU processes the CO₂ into LOX propellant
 - Paired with Methane brought from Earth
- Once LOX tanks are confirmed full, the crew lands on Mars
 - ISRU production is suspended, and the power system is switched over to crew life support functions
 - Some power needed for cryogenic propellant conditioning
- For solar-power system, dust storm disruption up to 120 sols is assumed

Acronyms

MAV

Mars Ascent
Vehicle

LOX

Liquid
Oxygen

ISRU

In Situ
Resource
Utilization

CO₂

Carbon
Dioxide



Study Approach

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1 Pre-cursor demonstration mission

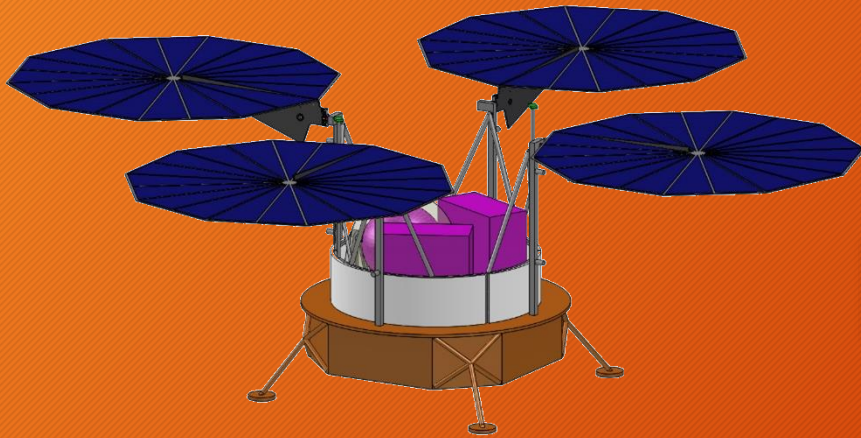
- Primarily an Entry-Descent-Landing demonstrator near the equator
- ISRU payload to demonstrate LOX production from atmosphere, at 1/5 scale of crewed mission
- Compare 10 kilowatt electric (kWe) Kilopower fission system to 3 solar options:
 - A. Daylight-only ISRU operation
 - B. Around-the-clock ISRU production (battery reserves for night)
 - C. Daylight-only, but 2x production rate to make up for night period

2 Crewed Surface Mission

- Cargo Phase: Around-the-clock production 23 t of LOX in 420 Earth days
- Crew Phase: Crew support functions + MAV keep alive and propellant conditioning (no ISRU)
- Evaluated the same crewed mission to two different landing sites
 - ✓ Jezero Crater, located 18.9° North
 - ✓ Columbus Crater, located 29.5° South
- Kilopower fission vs. [solar + batteries] vs. [solar + fuel cell]

kWe

kilowatt
(electric)



Vs.



ISRU Demonstrator

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Assumptions

Demonstrator Mission

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- **Land at Opportunity rover site at Meridiani (~2° south)**
 - Benefit of Opportunity's 12 years of actual solar array performance data, favorable night durations, and minimal seasonal variations
- **Mars environment based on Opportunity data**
 - Assumed one dust storm, 120 days in duration, maximum wind 20 m/s
 - Optical depth varies from 1.0 (clear skies) to 5.0 (dust storm)
 - Opportunity data: dust scatters light, so diffuse light during a storm is ~30-40% of direct light on a clear day
- **Average of 12 hours sunlight per sol**
 - But assume 10 hours/sol ISRU operation to allow for system warm-up



Dust storm time lapse as viewed by Opportunity



Fission Power Concept

Demonstrator Mission

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- ISRU system sized for 0.45 kg/hr LOX production with a goal of 4,500 kg
 - LOX tank only sized for 1,500 kg, with the balance vented overboard
- 10 kWe Kilopower unit providing 6.45 kWe (6.52 kWe at night)
 - Fixed, conical upper radiator requiring no deployment
 - 1,754 kg including 15% mass growth allowance and radiation shield sized to reduce crew exposure to <3 mR/hr within 500 m
- 6 m diameter landed footprint x 5.14 m dia. height
 - 2.61 m center of gravity height
 - 106 W keep-live power after landing
- 2,751 kg total payload mass
 - Including growth allowance

Kilopower is oversized for this application
But it's an opportunity to demo crew mission technology



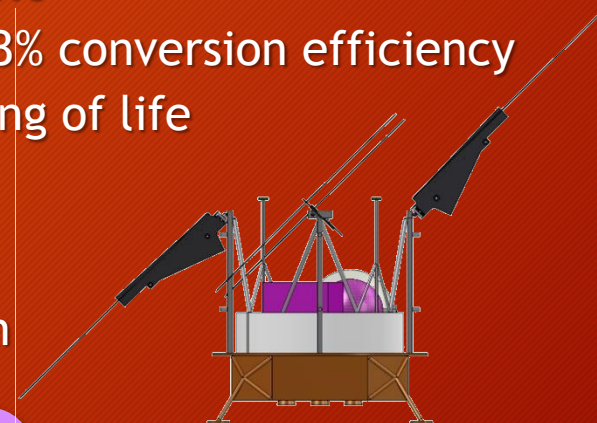


Solar Power Concepts

Demonstrator Mission

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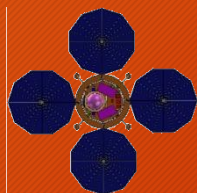
- Same ISRU assumptions as for fission power case
- 120V Orbital ATK UltraFlex™ arrays or equivalent
 - Inverted Metamorphic Multi-junction solar cells of 33% conversion efficiency
 - Measured at Earth distance solar flux, 28°C, beginning of life
 - 45° Gimbal for sun tracking and dust removal
- Panasonic cell type Lithium-ion batteries
 - 60% depth of discharge, 165 Watt-hours per kilogram



A

Daytime
Only

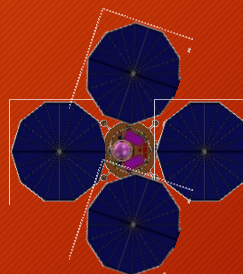
4 x 5.6 m
diameter
arrays



B

Around the
Clock

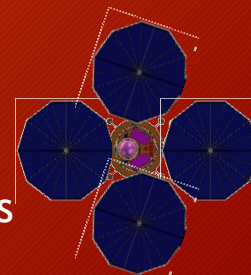
4 x 7.5 m
diameter
arrays



C

Daytime
Only 2x Rate

4 x 7.5 m
diameter arrays
+ 2x ISRU





Solar vs. Fission Comparison

Demonstrator Mission

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Closest “apples to apples” comparison

Option	Solar 1A: 1/5 rate Daytime Only	Solar 1B: 1/5 rate Around the Clock	Solar 1C: 2/5 Rate Daytime Only	Fission: 1/5 Rate Around the Clock Fission Power
Total Payload Mass (including growth)	1,128 kg	2,425 kg	1,531 kg	2,751 kg
Electrical System Mass	455 kg	1,733 kg	639 kg	1,804 kg
ISRU Subsystem Mass	192 kg	192 kg	335 kg	192 kg
Power	~8 kW Daylight	~8 kW Continuous (with 16 kW of arrays)	~16 kW Daylight	~7 kW Continuous
Solar Arrays	4 each x 5.6 m diameter	4 each x 7.5 m dia.	4 each x 7.5 m diameter	None
Night Production?	No	Yes	No	Yes
LOX Production	4.5 kg/sol	10.8 kg/sol	9.0 kg/sol	10.8 kg/sol
Time to Produce 4,400 kg LOX, including 120-Day Dust Storm Outage	1,098 sols	527 sols	609 sols	407 sols
ISRU On/Off Cycles	1,098	<5	609	<5



Observations

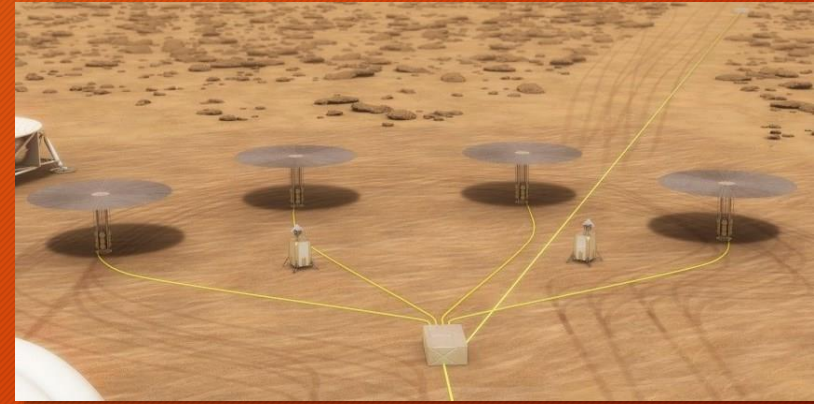
Demonstrator Mission

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- **Daytime-only solar power concept offers lowest landed mass**
 - High number of ISRU on/off cycles could pose reliability issues
- **Fission power was at a mass disadvantage in this trade**
 - 10 kW Kilopower was oversized for 7 kW application, plus mass included crew protection shield that wasn't necessary for demo
 - Equatorial site represents minimum solar power mass
 - ✓ Expect higher mass at other latitudes
- **All options fit comfortably within allowable payload limits**
 - So mass alone is unlikely to drive a decision for an equatorial mission
 - Power system selection probably depends on other factors
 - ✓ Technology investment strategies, program budgets, and risk mitigation needs for later crewed missions
- **Demonstrator mission solar power hardware costs are ~\$100M less than comparable fission power hardware costs**
 - Does not include technology development through Technology Readiness Level 6



Vs.



Crewed Mission

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Mission Concept of Operations

Crewed Mission

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	Expedition 1 <i>Four Landers</i>	Expedition 2+ <i>Three Landers per Expedition</i>
Cargo Phase	1. Power System + Cargo 2. MAV + ISRU 3. Mixed Cargo and Consumables	1. MAV + ISRU 2. Cargo and Consumables
Crew Phase	4. Habitat Module + Crew	3. Habitat Module + Crew

- Landers located no more than 1 km from each other
- Fission: Kilopower units remain together on/near the first lander
 - Robotic connections to subsequent landers
 - Power can be disconnected when a lander is no longer in use
- Solar: arrays on every lander, at least through Exp 3
 - All landers connected into a power grid
 - Remain connected even if lander is no longer active



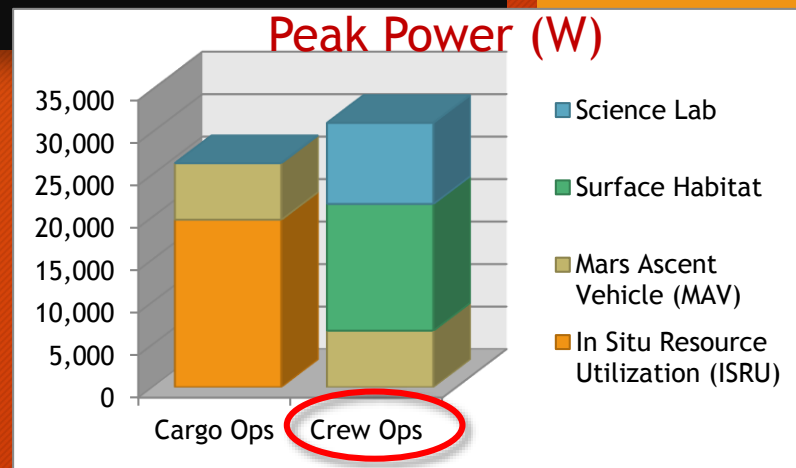
Surface Power Needs Crewed Mission

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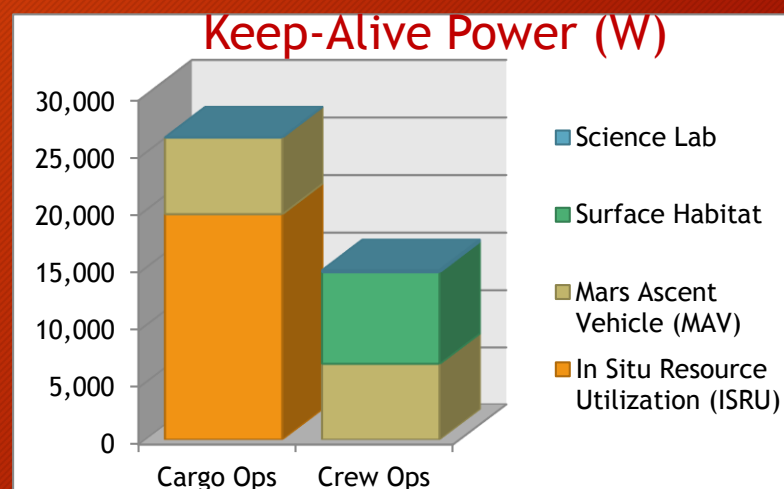
ISRU: Produce 22,728 kg of LOX in 420 Earth days

Element	Peak Power Needed (W)		Keep-Alive Power Needed (W)	
	Cargo Phase	Crew Phase	Cargo Phase	Crew Phase
ISRU	19,700	0	19,700	0
MAV	6,655	6,655	6,655	6,655
Surface Habitat	0	14,900	0	8,000
*Science Laboratory	0	9,544	0	174
Total	26,355	31,099	26,355	14,829

*Optional element shown with all systems running. Assume power can be phased to stay below cargo ops total peak



Note that eliminating ISRU doesn't reduce overall surface power need





Fission-Powered Option

Crewed Mission

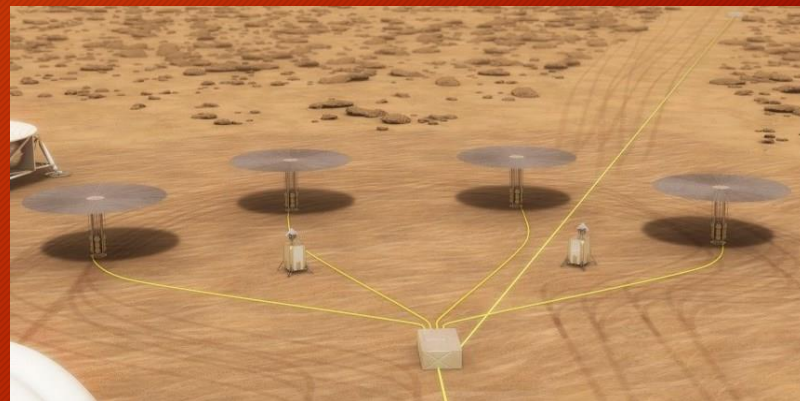
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- Four each 10-kWe Kilopower units would provide up to 35 kWe continuous power for all mission phases at either hypothetical landing site
- Fission power generation mass is 9,154 kg
 - Includes one spare Kilopower and mass growth allowance
 - Not including power farm-to-lander Power Management and Distribution
- Up to 1,038 kg PMAD could be needed on the Lander 1, depending on whether Kilopowers are relocated and whether any other cargo requires 1,000 - 120 VDC conversion
 - Landers 2, 3 and 4 would each require 1 km spool of high voltage cabling, connectors, and voltage converters

PMAD

Power
Management
and
Distribution

Description	Lander 1	Lander 2, 3, 4	Expedition 1 Fission Power Generation Total
Power Generation			
50 kWe Kilopower	8,769	0	
Power Management			
Stirling AC Cable	62.4	0	
Stirling Controller	322.4	0	
FISSION SYSTEM TOTAL	9,154	0	9,154 kg



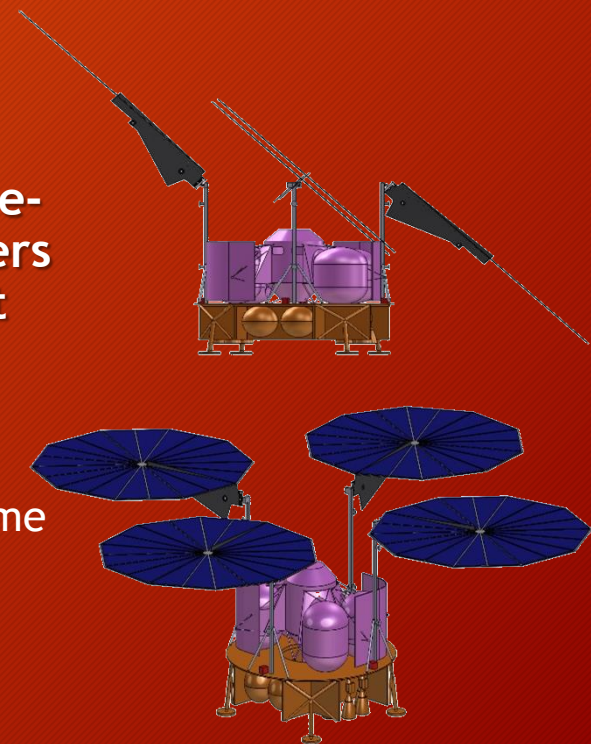


Solar-Powered Option

Jezero Crater Crewed Mission

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- Study team estimated that all four Expedition 1 landers would require four each 12 m diameter UltraFlex™ arrays or equivalent
 - Deployed on a 9.1 m diameter lander would extend the overall footprint to ~33 m
 - With arrays in neutral position on a 2.66 m high lander deck, overall height was ~9.69 m
 - Deploying arrays high minimizes interactions with surface or payloads
 - Gimbals help shed dust
 - Lander deck provides stable operating platform
 - ✓ Allows arrays to be brought on-line quickly
- Under nominal Jezero Crater conditions, around-the-clock propellant production with the first two landers requires 34.2 kW during the day and 35 kW at night
 - During dust storm, power would be reduced to 10,985 W during the day and 11,728 W at night.
 - Once crew arrived, combined loads of the first four Expedition 1 landers were 31,915 W during nominal daytime operation and 26,790 W at night
 - Loads drop to 22,945 W during the day, and 24,060 W at night during a dust storm





Solar-Powered Option

Jezero Crater- Expedition 1

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Description	Lander 1	Lander 2	Lander 3	Lander 4	Jezero Crater Expedition 1 Solar Power Generation <u>and</u> <u>Storage</u> Total
Electrical Power Subsystem	4,890	1,512	1,512	1,512	
Power Generation	1,321	1,321	1,321	1,321	
Lander Internal Power Management and Distribution	401	192	192	192	
Energy Storage	3,168	0	0	0	
Structures and Mechanisms	660	476	476	476	
Secondary Structure	416	418	418	418	
Mechanisms	244	59	59	59	
Thermal Control (Non-Propellant)	61	45	45	45	
Active Thermal Control	2.4	3.4	3.4	3.4	
Passive Thermal Control	41.8	42	42	42	
Semi-Passive Thermal Control	16.8	0	0	0	
SOLAR POWER SYSTEM	5,611	2,034	2,034	2,034	11,713 kg

Does *not* include lander-to-lander PMAD
Mass grows to 12,679 kg at Columbus Crater

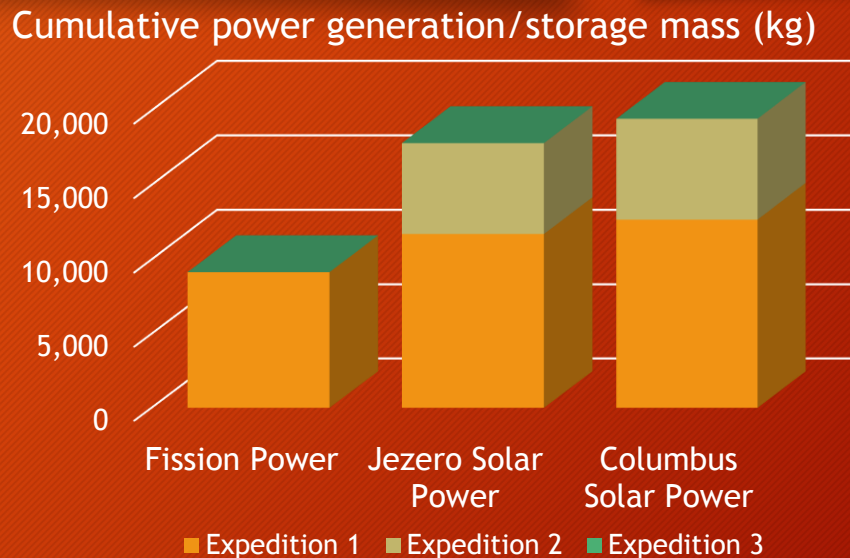


Solar vs. Fission Comparison

Crewed Mission

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- **Mass:** Expedition 1 comparison doesn't tell the whole story
 - All fission power arrives with Expedition 1, but solar power performance doesn't catch up until Expedition 3
 - Extrapolate through 3 expeditions for apples-to-apples comparison
- **Performance:** comparable by Exp 3
- **Robustness:** fission power is more tolerant of dust, but the distributed solar power network is more tolerant to cable damage
 - Allows quick post-landing power, but arrays on MAV lander will have to be removed before MAV departs
 - ✓ Additional risk for crew/robotics to handle large arrays close to the MAV
- **Service Life:** 12-year Kilopower service life is probably about the same as solar power's rechargeable battery life





Observations

Crewed Surface Mission

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- **50 kWe of fission power is ~20% less landed mass than 35 kW of solar power generation and storage for the 1st Expedition to Jezero Crater**
 - Not including lander-to-lander PMAD for either option, which could add a metric ton per lander
 - ✓ All solar powered landers become part of an integrated network, so they have to remain cabled together, even after cargo has been unloaded
 - ✓ Fission system only needs to be cabled to landers with active surface payloads
 - Assumptions will alter the analysis: landing site, propellant production rate, time available to make propellant, dust storm duration, transmission voltage
- **By the 3rd Crew Expedition, cumulative solar array mass is more than 2x fission power mass**
 - But enough solar array area will have been accumulated to accommodate a 120-sol dust storm with little disruption
- **Mass differential is greater at Columbus Crater landing site**



Conclusions

Solar vs. Fission Mars Surface Power

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- Solar-powered crew surface mission is more feasible under EMC than previous mission concepts
- Solar-powered crew surface mission is certainly *possible*, at least for some latitudes
 - Forward work to evaluate all landing sites of interest (up to 40° N)
- **Advantages and Disadvantages**



Solar: High technology readiness, lower cost, and quick to switch from on-board stored energy to surface power; but high mass penalty may limit landing site options, and higher risk during a storm



Fission: Reliable, lower mass for most landing sites, same mass regardless of site, season, day/night, or weather; but lower technology readiness and higher development cost

- **Either power system will require substantial technology development and flight hardware investment**

A vertical poster for NASA's Journey to Mars. The top half shows a close-up of a rover's tire tracks on the reddish-brown surface of Mars. The bottom half shows a close-up of a rover's solar panel array. The text "NASA'S JOURNEY TO MARS" is prominently displayed in the upper left, with the "A" in "MARS" stylized to include a small image of Mars. The NASA logo is in the upper right. The hashtag "#JOURNEYTOMARS" is in the lower left.

NASA'S JOURNEY TO

MARS



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Questions?

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